Space Launch System Ascent Aerothermal Environments Methodology

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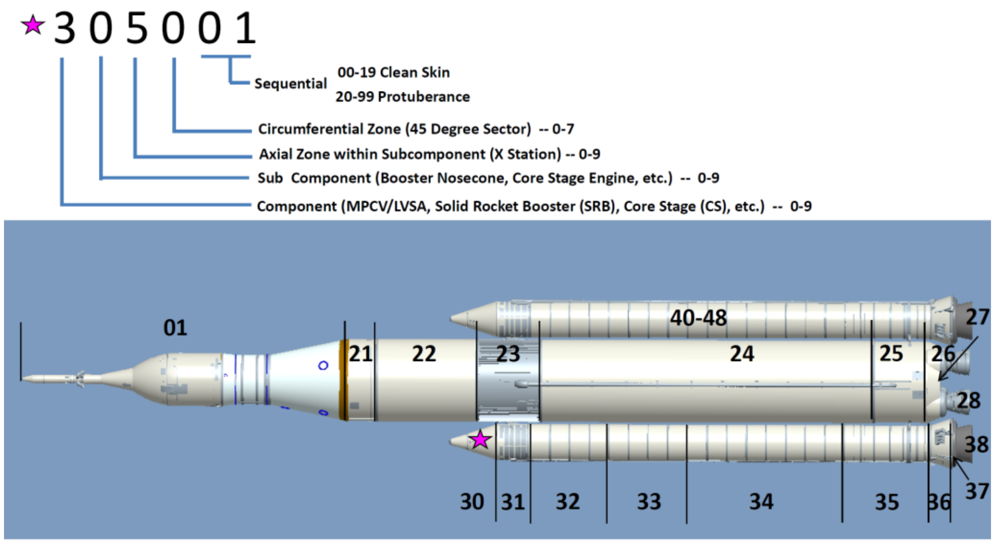
Overall Aerothermal Analysis Approach

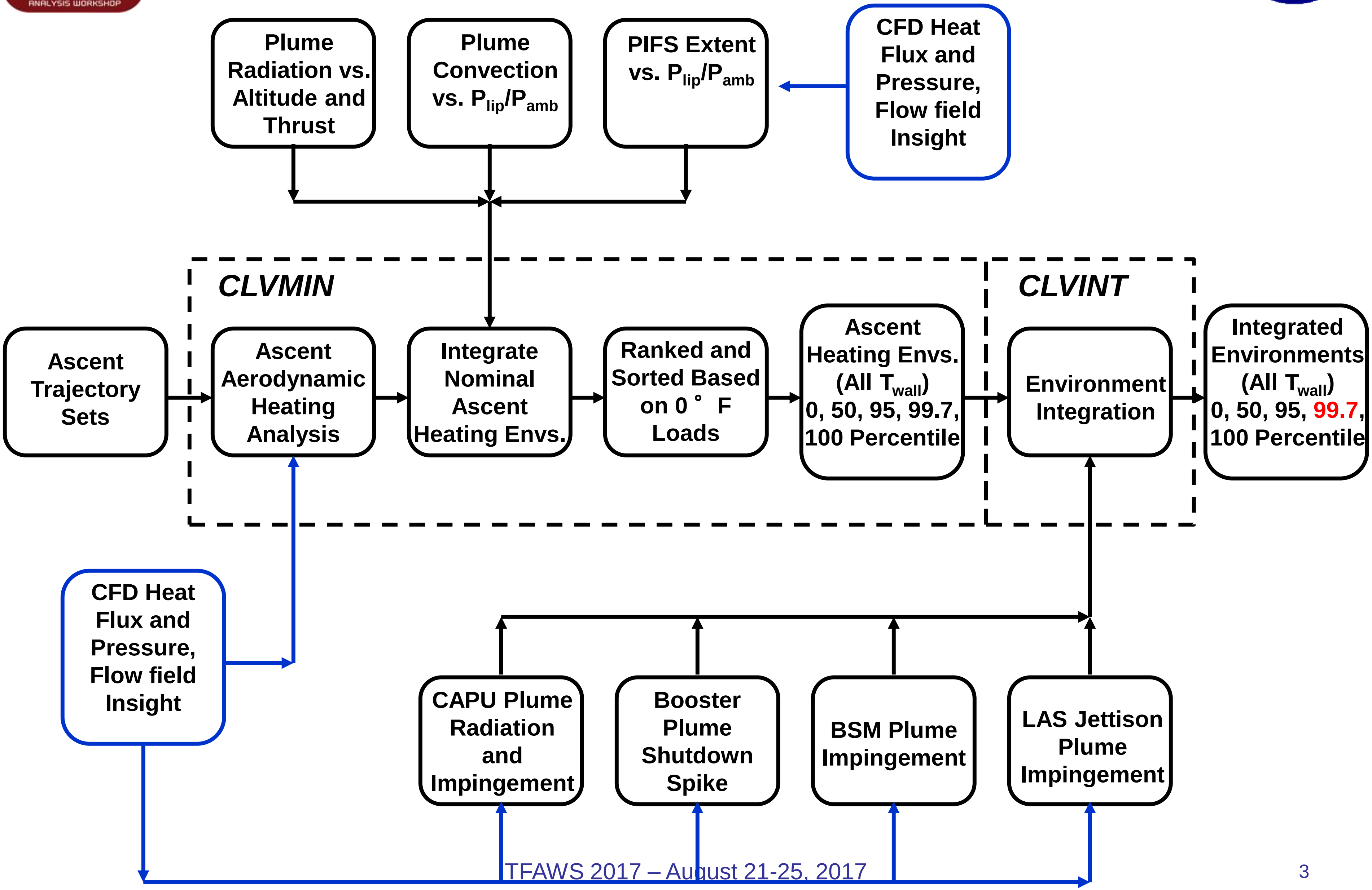
- Environments are generated at a large number of particular locations (body points) on the vehicle
- Three key inputs needed to develop aerothermal environments
  - Vehicle geometry
  - Engine / motor operating parameters
  - Trajectories

Body Point Numbering Convention



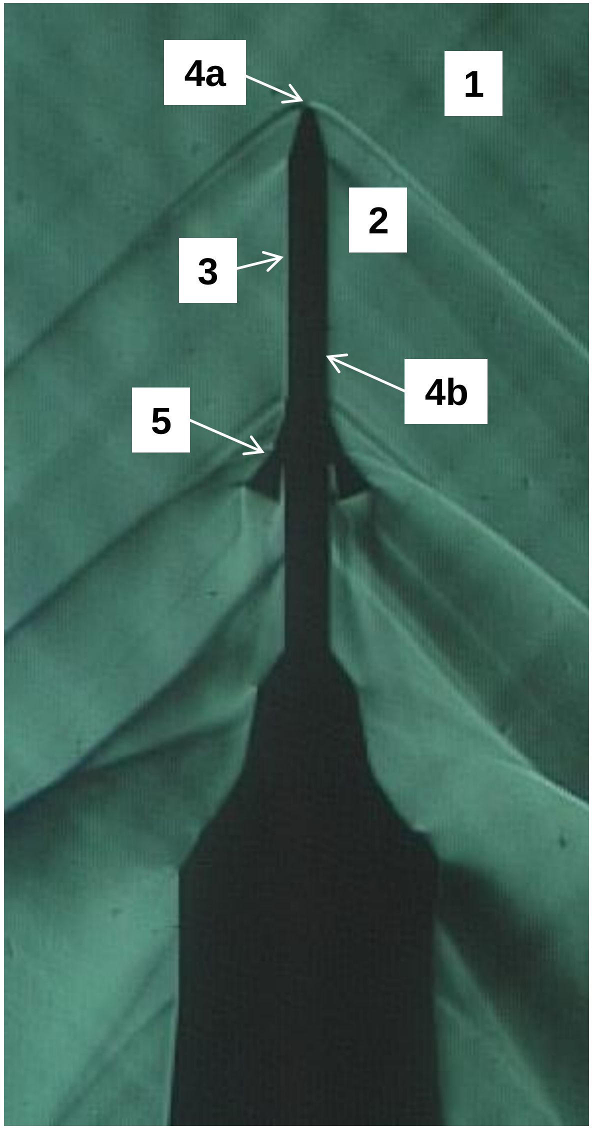
- Current environments are statistical (99.7% highest at each location)
- Block 1 SLS aerothermal environments are documented in SLS-SPEC-044-02

SLS Aerothermal Environments: Processes and Codes



SLS Aerodynamic Heating

- CLVMIN is an enhanced version of the MINIVER code
  - Improved local condition determination
  - Modified to generate statistical environments from trajectory sets

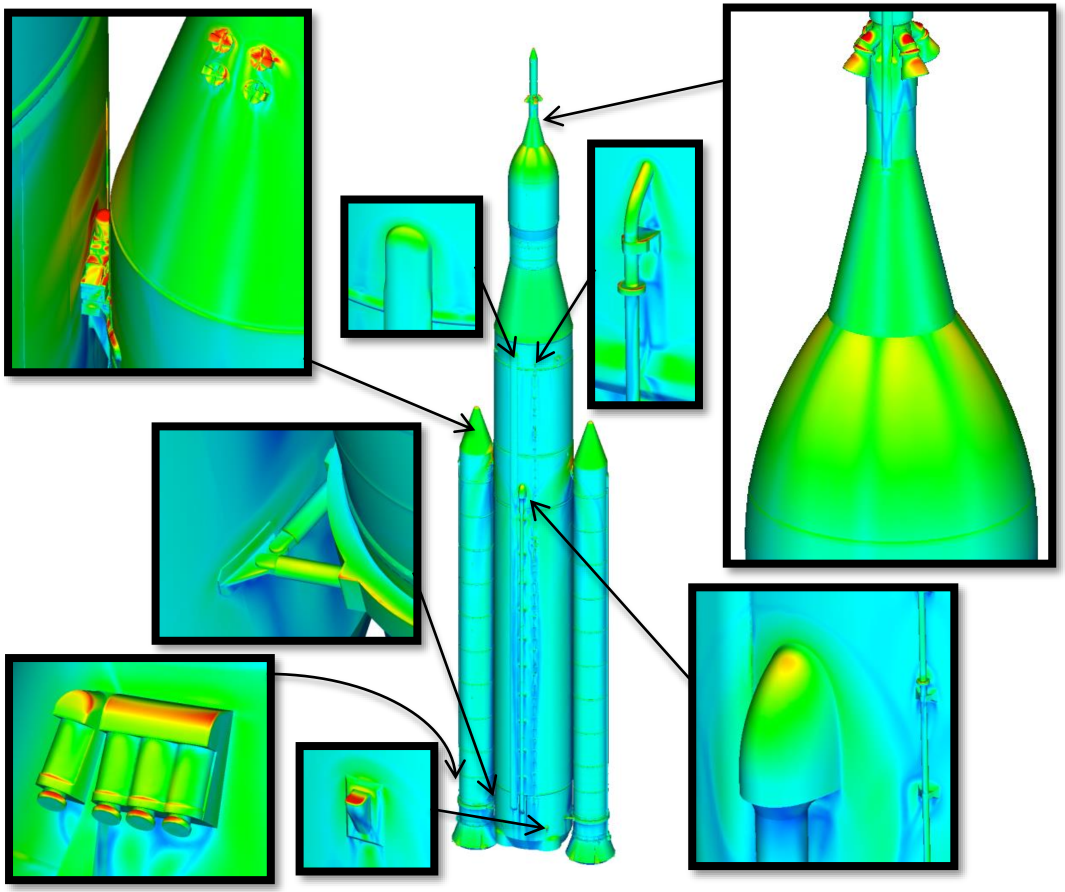


1. Flow field: Free stream trajectory conditions (P, T, Mach, etc.) are processed through appropriate shock(s) using compressible flow equations
2. Flow regime: Determine if continuum / transitional / rarefied / free molecular based on Mach, Reynolds #
3. Boundary layer: If continuum flow, determine if turbulent or laminar boundary layer conditions based on Mach, Reynolds #
4. Heating Model: Apply depending on geometry, examples: spherical – 4a (i.e. Fay & Riddell), flat plate – 4b (Spalding-Chi w/ Mangler transformation)
5. Protuberance Factor: If needed, apply empirical or analytical amplification factor (h_i/h_u)

*Significant use of empirical amplification factors for core stage and booster geometry with extensive flight/wind tunnel testing history

SLS Aerodynamic Heating: Protuberances

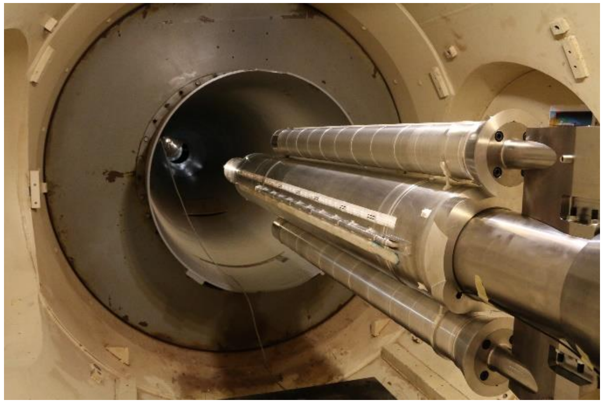
- Many similarities, but also some key differences, compared with Shuttle
- Much of current Block 1 design informed by CFD cases run in DAC-3R
  - SLS-10005 OML
  - TD3 6-DOF trajectory sets
  - Altitudes from 50-160 kft
  - Mach numbers from 2.0-4.5
- Loci/CHEM CFD code
  - ~360M Cells (unstructured)
  - RANS turbulence modeling
- H_i/H_u factors developed from solutions using protuberance heating and local “clean skin” heating

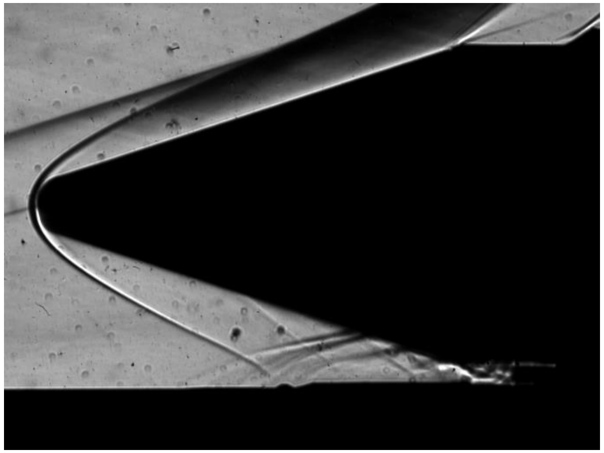


- Verification phase for Block 1 vehicle (VAC-1) is currently being informed by CFD using an updated SLS-10008 OML

SLS Aerodynamic Heating: Verification

- Block 1 SLS aerodynamic heating environments for clean skin and protuberances were recently validated using measurements from the ATA-003 Phase 1 aerodynamic heating test conducted at CUBRC in 2016
  - 3% model scale
  - 176 heat flux gauges and 28 pressure gauges
  - 21 test runs at Mach 3.5-5.0
  - Schlieren and temperature sensitive paint imaging
- Heat flux measurements indicate that vast majority of SLS aerodynamic heating design environments are either accurate or conservative
- Some exceedances noted on Core Stage / Booster forward and aft attach struts – both of which are very complex flow fields. Updated aft attach environments have been sent to Booster.
- CFD comparisons with test data inform best practices
- Block 1B SLS configurations with additional sensors were tested in ATA-003 Phase 2 conducted in 2016-2017 – will inform Block 1B DAC-2 currently underway

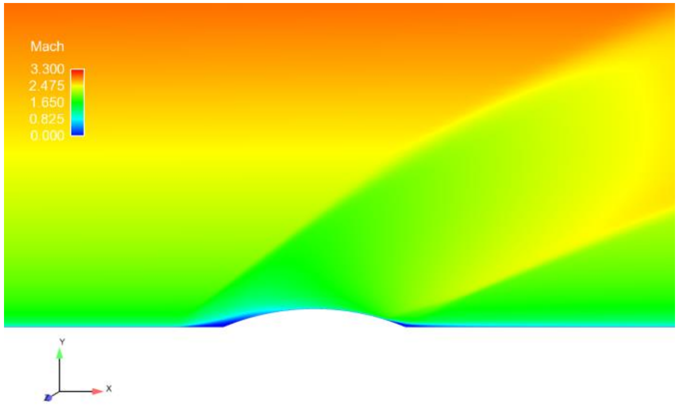




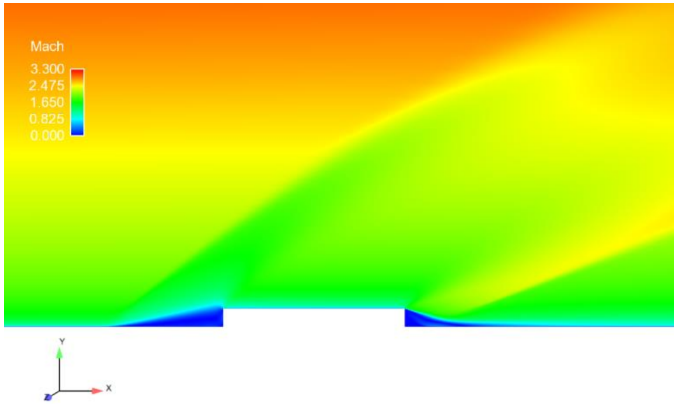
SLS Aerodynamic Heating: Small Protuberances

- SLS small protuberance methodology is based on results from several hundred Loci/CHEM 2-D RANS CFD cases
- Intended to provide simple estimate of enhanced heating for small (< 0.5 inch) protuberances significantly smaller than the local boundary layer thickness
- Results for relatively smooth protuberances show good agreement with the semi-empirical formula reported by Jaeck, 1966 in flow scenarios the formula was intended for, but important differences in scenarios it was not

Circular Arc Protuberance

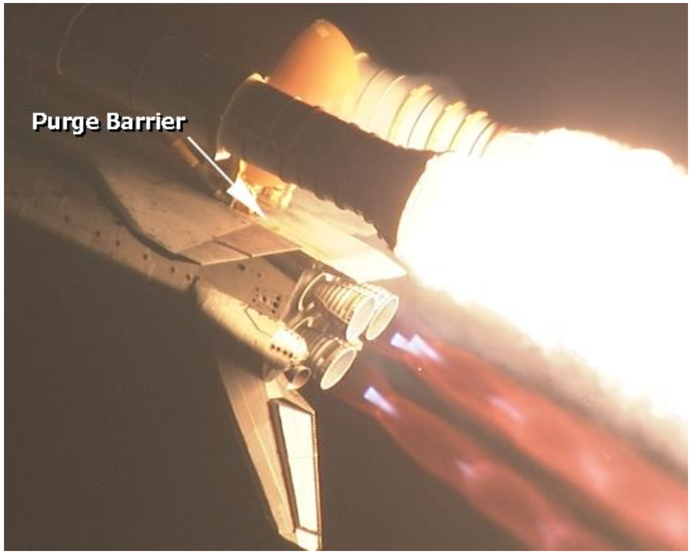


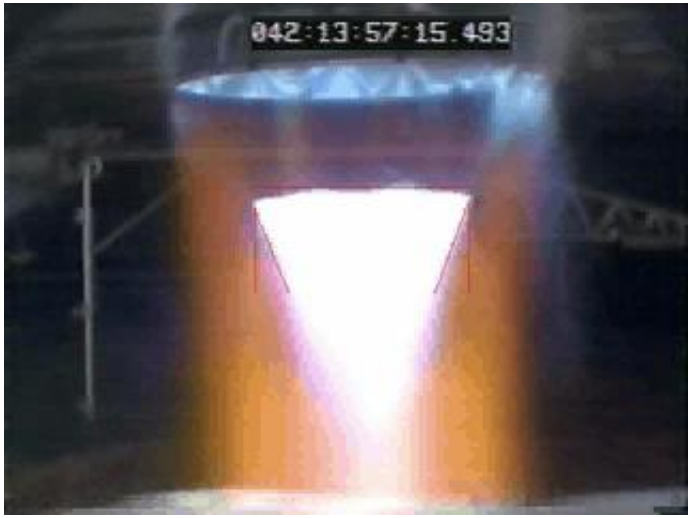
Step Protuberance



SLS Plume Radiation Heating

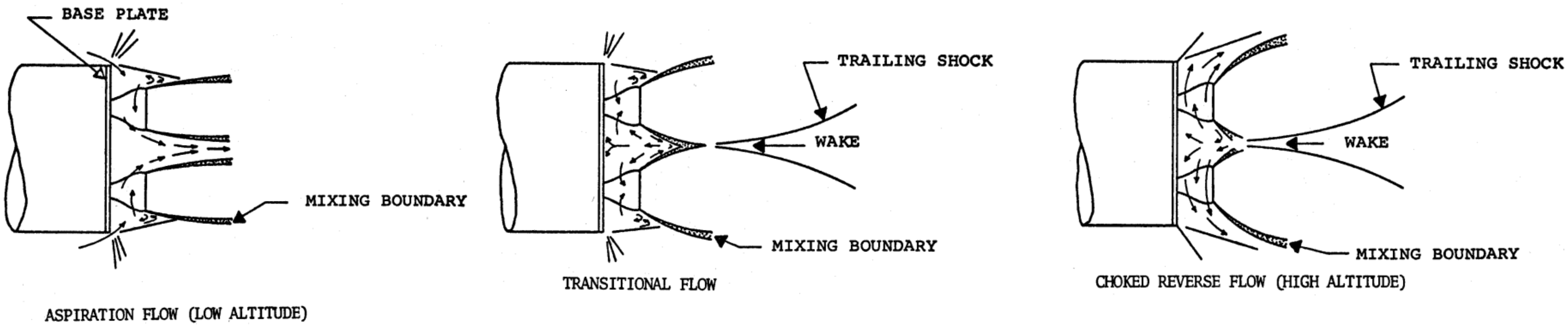
- Though both the RS-25 engines and the five segment solid rocket Boosters are derived from Shuttle, the engines and Boosters are now in much closer proximity
- Plume radiation heating primarily driven by H_2O in RS-25 plume Mach discs and Al_2O_3 particles in booster exhaust – most significant early in flight
- Significant heat load for areas of the vehicle base which have a clear view of the Booster and RS-25 plumes
- Typically calculated using two step process - calculate plume using CEC/RAMP2/SPF3, then model radiation:
  - Reverse Monte-Carlo (RMC) code for multi-phase (Booster) plumes
  - Gaseous Radiation (GRAD) code for gas-only (RS-25) plumes
- Radiation calculated at various altitudes for SLS ascent
- “Shutdown spike” is captured



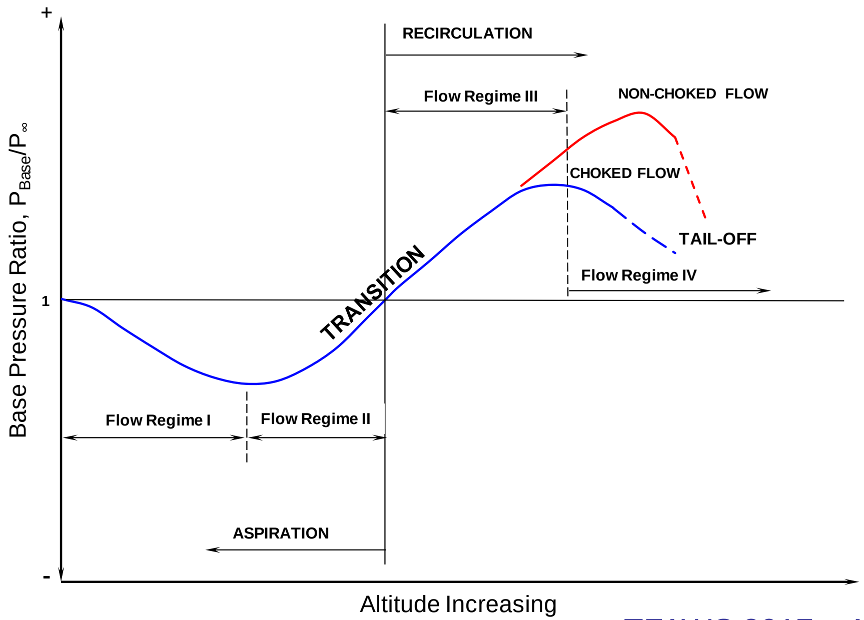


SLS Plume Convection Heating

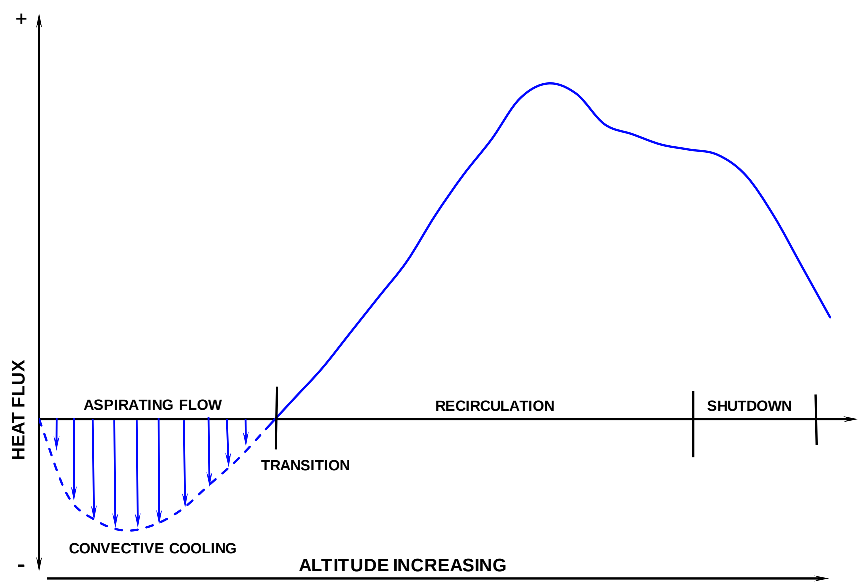
- Base pressure and convection change with altitude and Mach number



ASCENT BASE PRESSURE TRENDS

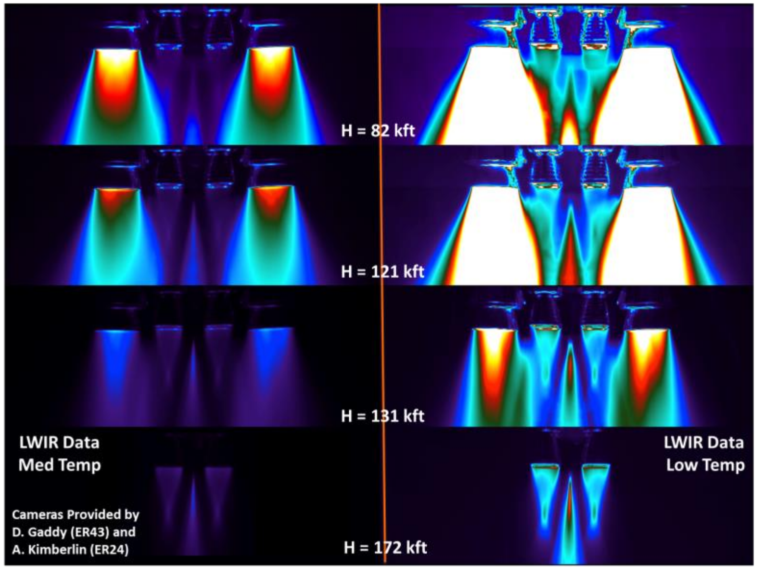


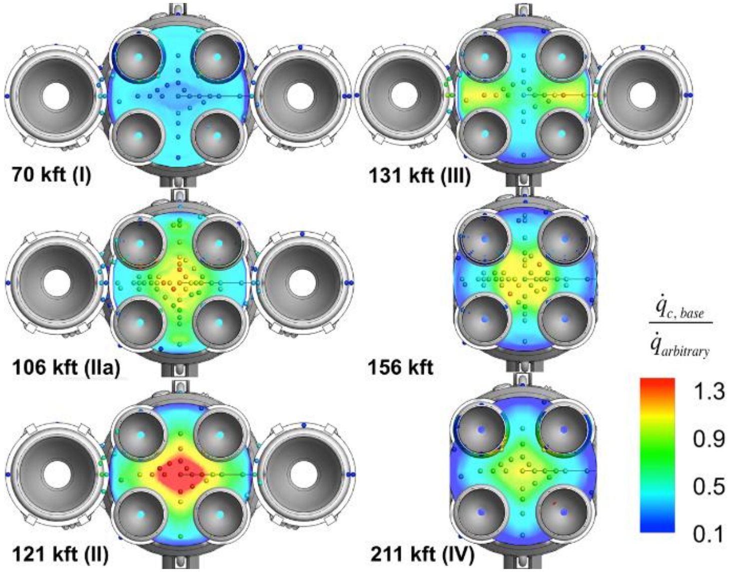
ASCENT BASE CONVECTION TRENDS



SLS Plume Convection Heating: ATA-002 Test

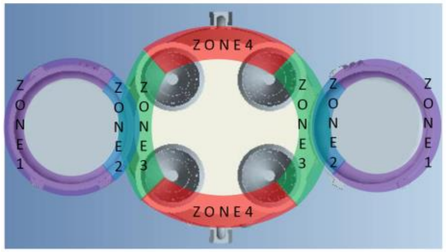
- Due to completely different base and engine configuration for SLS, compared to Shuttle or Saturn V, a subscale ATA-002 plume convective heating wind tunnel test was conducted at CUBRC as part of SLS development in 2013-2015
  - 2% model scale
  - 169 heat flux gauges and 37 pressure gauges
  - 76 tests were run at simulated altitudes of 50-211 kft, and Mach 2.7-5.0
- To reduce risk, a pathfinder subscale engine / motor development effort was conducted before the main plume convection heating test was run
- Updated plume convection environments were derived from test data and baselined in SLS-SPEC-044-02 documentation in late 2015
- Test data exhibited significant differences from Shuttle (e.g. base heat shield, engine thermal blankets, engine nozzles)
- CFD comparisons with test data inform best practices for these types of environments

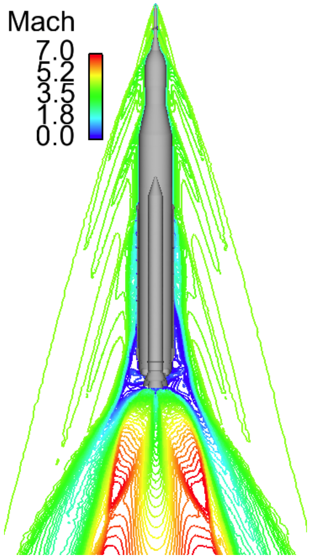




SLS Plume Induced Flow Separation (PIFS) Heating

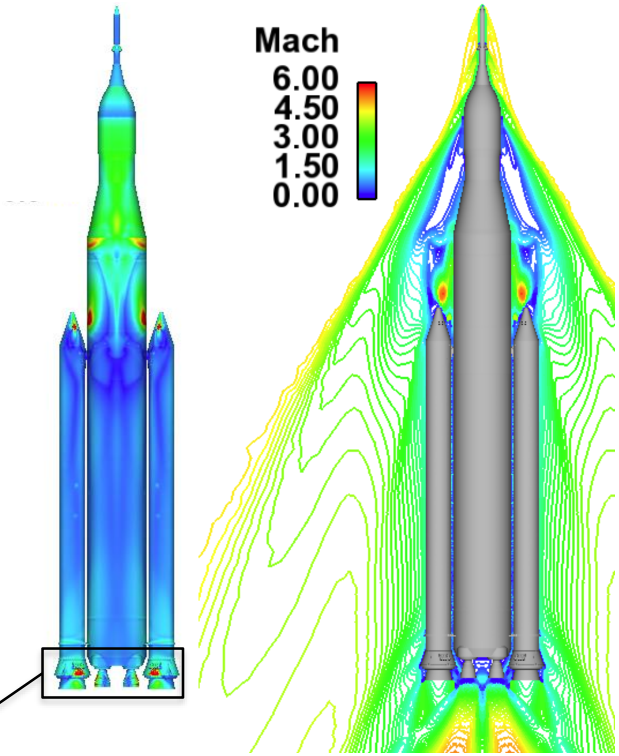
- PIFS is closely related to plume convection heating, and occurs as the recirculating plume gases cause boundary layer separation on the vehicle at high altitude
- Classic example is Saturn V
- Current SLS PIFS heating methodology predicts heating based on Shuttle and Saturn data
- PIFS heating is applied to the Core Stage and Booster by circumferential zones using RS-25 engine and Booster P_{lip} / P_{amb} ratio
- The phenomenon is also observed in Loci/CHEM CFD solutions – comparisons will be made moving forward



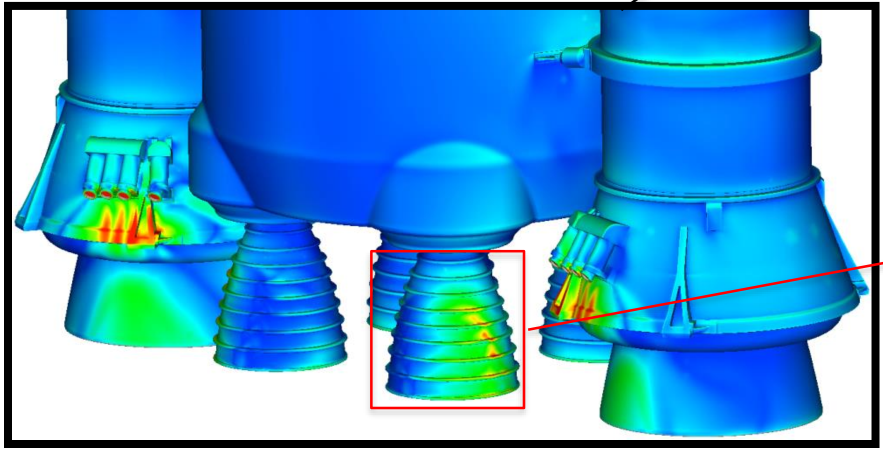


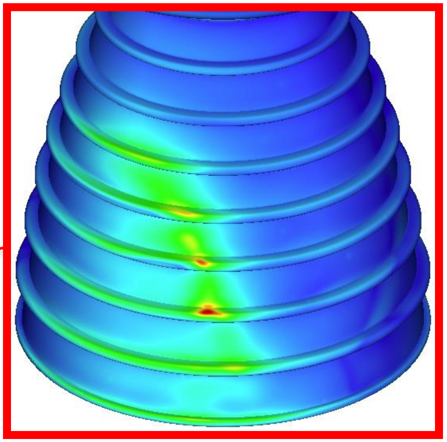
SLS Booster Separation Motor (BSM) Plume Impingement Heating

- Forward BSM plume impingement environment is similar to Shuttle scenario, but aft BSM environment is completely new for SLS
- Loci/CHEM unstructured CFD code
  - ~120M cell grid assumes flow field symmetry
  - RANS turbulence modeling and frozen chemistry
  - Plume gases modeled as a single equivalent gas
  - Four cases completed at 0.02, 0.2, 0.4, and 0.6 seconds after initiation of booster separation
- High confidence in direct plume impingement heating prediction from CFD, based on Constellation-era tests and Ares I-X flight data
- Recent CFD analysis has analyzed aft BSM rotation options to enhance separation clearance



*Orion MPCV Launch Abort System (LAS) Jettison Motor (JM) plume impingement environments also derived from CFD

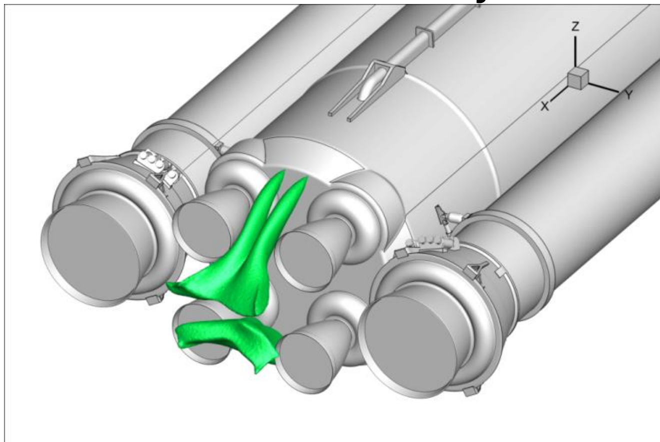




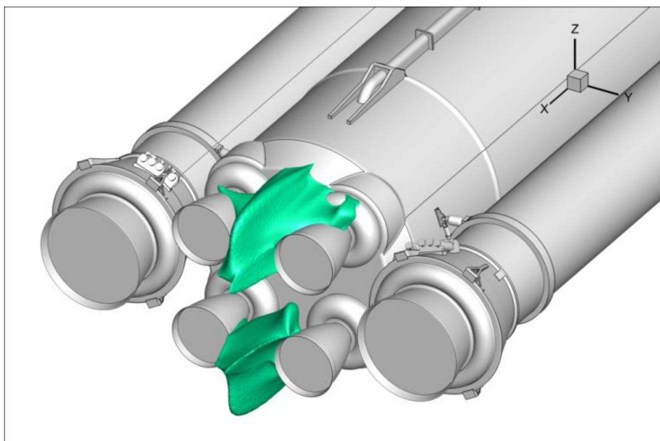
SLS Core Auxiliary Power Unit (CAPU) Plume Heating

- New environment for SLS - CAPU system drives hydraulic fluid used for RS-25 gimballing and throttling
- System is powered in flight by H_2 gas tapped off from main propulsion system
- Four exhaust ports in Core Stage base emit the H_2 gas in a “low” flow state for most of the time, but also periodically pulse into a “high” flow state
- Loci/CHEM CFD solutions
  - ~200M cell grid
  - 6 species (O_2, N_2, H_2, H_2O + 2 equivalent plume gas species)
  - Fast $2H_2 + O_2 \rightarrow 2H_2O$ chemistry assumed
  - Solutions through Boost Stage flight completed in 2015
- Convective heating environments developed from analysis and simplification of these solutions
- Radiative heating environments developed from these solutions and GASRAD code
- Combined convective and radiative environments integrated into the final design environments

Iso-surfaces of 10% H_2O Mass Fraction RS-25 and Booster Plume Exhaust Not Shown for Clarity



Mach 0.1, 600 ft



Mach 2, 51,000 ft

Summary

- Aerothermal environments for the vehicle are integrated from several different sources of heating:
  - Aerodynamic heating
  - Plume radiation heating
  - Plume base convection/recirculation heating
  - Plume induced flow separation heating
  - Plume impingement heating
  - CAPU plume/flame heating
- Experience and test data obtained during Block 1 SLS development is aiding work on Block 1B vehicle